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# ELECTROMAGNETIC AND PLASMA EFFECTS IN THE IONOSPHERE INDUCED BY ROCKET LAUNCHES

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## Introduction: To save the data of early active experiments

Geophysicists from former SU performed an impressive number of observations on active impact on geophysical media. However, an overwhelming part of these results was published in reports with a limited circulation, practically unavailable to world geophysics. In many of those unique experiments the effects were found that still remain unappreciated from a scientific point of view. A repeating of most of those experiments is impossible under current financial support of science. Thus, though a significant part of early experiments was lost, still there are possibilities to introduce into scientific analysis at least part of them. With this goal in mind, here the results of observations in 80-ties of the ionospheric plasma and electromagnetic field disturbances during rocket launches are presented.

The rocket launches of space vehicles are sources for intensive disturbances of the ionosphere [*Zasov et al.,* 1977; *Karlov et al.,* 1980; *Gorely et al.,* 1994], and, gradually, they are coming to be the main factor of anthropogenic impact upon the near-Earth space [*Burdakov et al.,* 1990]. The ejection of combustion of rocket propellant products results in a locally distorted photochemical balance and considerable (up to 1-2 orders) and prolonged decrease in the ionospheric plasma density ("water hole") [*Booker,* 1961; *Felker and Roberts,* 1966; *Mendillo,* 1988]. The "water hole" is not a localized in space or time effect. Numerical simulation of consequences of the injection of water and other reagents into the ionosphere [*Vlasov et al.,* 1990; *Kolomiytsev et al.,* 1991; *Kozlov et al.,* 1992] indicates on the possibility of very long occurrence of an "ionospheric hole" in the maximum of F2 layer, up to the sunrise. At low latitudes ($L$<2) the coupling between the conjugated ionospheres starts to show itself. The leakage of the Shuttle-induced disturbances into the conjugate ionosphere was indeed reported by *Danilushkin et al.* [1988].

Distant transfer of disturbances, generated by rocket engines, can be done by the acoustic and gravity waves [*Arendt,* 1971,72]. As a result, a region of the ionosphere turbulization spreads as far as several thousand km from a launching site [Noble, 1990]. The formation of large-scale cavity with the 60% decreased total electron content (TEC) was observed by *Mendillo* [1975] after the launch of Saturn V rocket at altitude above 440 km using the Faraday rotation of radio-signals from geostationary beacon. This cavity above the East cost of USA had a scale ~$10^3$ km and existed for 4-6 hours. Even relatively small geophysical rockets produce noticeable disturbances of the ionospheric plasma in the wake region [*Abdu et al.,* 1988]. The artificial ionospheric disturbances produced at the active phase of the ballistic missile trajectories give possibility to radisound the missile traces at distances up to few thousands of km [*Akimov et al.,* 2000]. The probable stimulation of MHD disturbances in the ionosphere by rocket launches was verified with the ground high-sensitive search-coil magnetometer observations by *Pilipenko et al.* [2006]. Sonograms for the periods of the strategic missile launches at Plesetzk site revealed the occurrence of short-lived (~3-5 min) emissions in the frequency range 0.5-2.5 Hz at stations in Finland in ~20% of events. Probably, the appearance of ULF emissions is related to the trapping of the part of rocket-stimulated MHD disturbances into the ionospheric waveguide.

The problem of the disturbance transfer into the upper ionosphere and magnetosphere has not been studied experimentally in a comprehensive way yet, although possible physical scenarios of such a transfer had been discussed [*Kelley et al.,* 1980]. Following are the preliminary results from the attempt to detect the effects from rocket launches according to the observational data from the plasma and wave detectors on low-orbiting satellites.

## Wave measurements made onboard Aureol-3 satellite

The set of this satellite apparatus comprised an instrument for examination of electric and magnetic fields in the frequency range 50 Hz - 20 kHz [*Berthilier et al.,* 1982]. Two components of the electric field, $E_Z$ and $E_H$, with sensitivity 0.5 mV/Hz were measured. The $X$ axis is directed along the satellite speed, $Z$ axis is away from the Earth, and $H$ axis supplements them. The experimental complex comprises filter sets for obtaining survey information about emission spectra. The narrow-band filters of the spectrum analyzer for noise emissions were tuned to the central frequencies 0.14, 0.45, 0.8, 4.65 and 15 kHz. Magnetic component of emissions were detected by three induction sensors with the sensitivity ~$10^{-5}$ nT/Hz. The events were selected when the satellite, within an hour's delay, crossed the invariant latitude of the rocket launching site during geophysically quite periods.

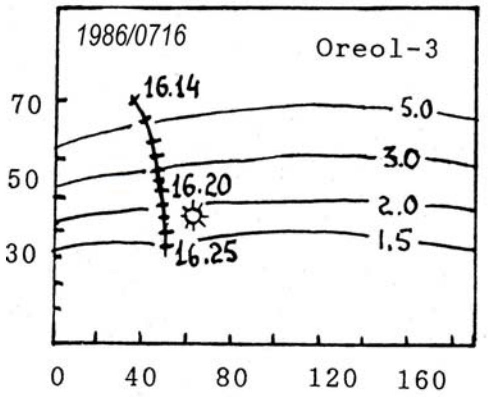
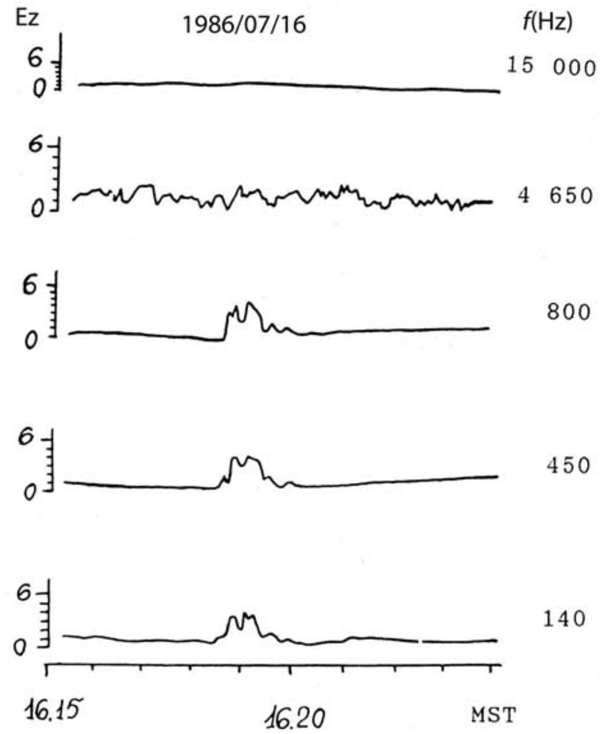



**Fig.1.** (a) Ionospheric projection of the Aureol-3 orbit on 16.07.1986. Geographic coordinates are indicated along axes, solid lines denote the projection of L–shells, asterick (∗) indicate the launch site at 15.30 Moscow time.
(b) Variations of Ez electric component amplitude of ELF emission 140-15000 Hz (in telemetry units) at outputs of band-pass analogue filters.




**July 16, 1986 event.** The rocket was launched on 15:30 (here and thereafter the Moscow standard time). Aureol-3 crossed the invariant latitude of the launching site about 50 min after the take-off. Fig. 1 (left-hand panel) shows, in geographical coordinates, the projection of the orbit which passed west of the site by ~18$^o$. At that time the satellite height was ~1300 km. Fig. 2 (right-hand panel) shows the fragments of the analog data recordings. The invariant latitude of the starting point corresponds to L=2, where the intensity of natural ELF-VLF emissions is low and usually does not exceed the detector's noise level. The increase of the emission amplitude can be seen at the time interval 16.18.30-16.22.00, which corresponds to the pass near the launching site. The variations of the $E_Z$ component clearly displays a surge of the emission intensity, especially at the frequency of 140 Hz. The emission seems to be electrostatic, since the magnetic component is seen vaguely at the noise background (not shown). At the higher frequencies, the electric component is also prevailing. At the frequencies of 4650 Hz and higher the filter channels did not respond to the take off. The surge of the emission intensity was also noted in the variations in the $E_H$ component (not shown) and in the output of wide-band filters which measured the ELF $E_H$ and $E_Z$ components. The short-lived increase in noise intensity detected at quiet time at latitudes where almost no natural emissions occur may be attributed to man-made disturbance.

**July 17, 1986 event.** The rocket was launched at 15:30 Moscow time. The projection of the orbit of the Oreol-3 satellite intersected the invariant latitude of the take off about 22 min after launching westward of the launching point by 12$^o$ (Fig. 3, upper panel). The variations in intensity of the $E_Z$ component at 15:50-15:52 display a surge in emission intensity pronounced most at $f$~140 Hz. In the variations of emission at the frequencies of 450 and 800 Hz, the intensity surges were flagged by elevated background noise. Also, like in the event of July 16, no emission surges were noted at frequency 4650 Hz and higher.
Thus, upon the transition of satellite through the geomagnetic shell conjugated to the rocket take-off, the burst of ELF noise have been detected. In all events, the recorded emissions were mainly electrostatic with the highest power at frequencies about few hundred Hz.

## "Waterhole" above the launching site: plasma measurements on-board Kosmos-1809

The data of satellite Kosmos-1809 may be considered as an observational support of the effect of the "plasma hole" formation in a flux tube over the regions of the powerful rocket launches. This satellite has a near-circular polar orbit with altitude $h$=950 km. The satellite detected the effect of "water hole" above the launching site of the orbital station MIR on 1991/05/18. Above the region of the rocket launch a drastic decrease of the electron density $N$ was observed (Fig. 2, upper plot). At the boundaries of the "plasma hole" intense fluctuations of electron density, $\delta N/N$, have been observed with amplitudes up to 10-18% (Fig. 2, bottom plot). The disturbed region of the ionosphere was shifted somewhat southward from the vertical projection of the rocket launching site.

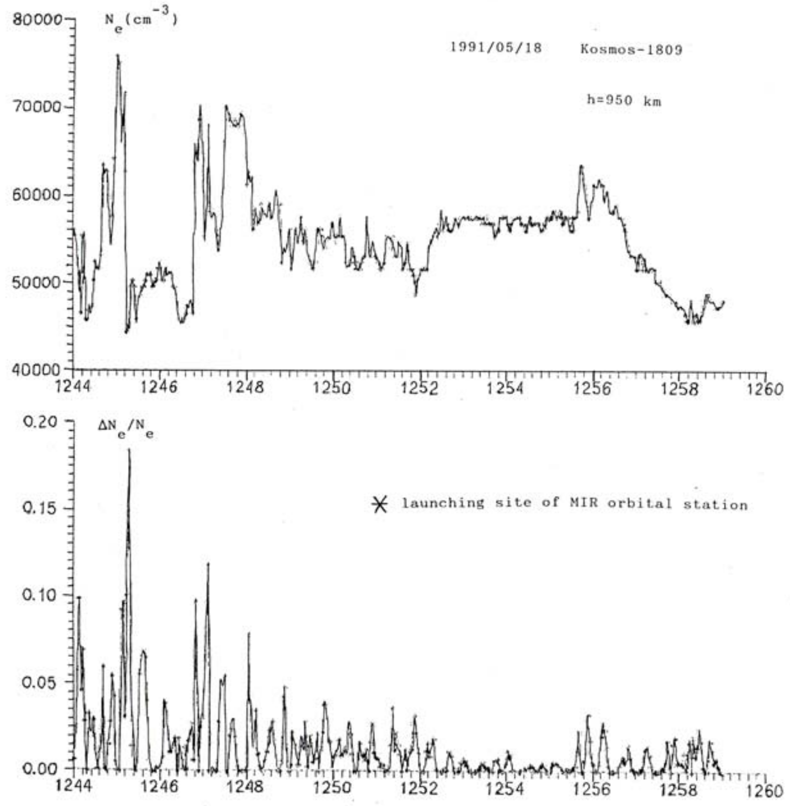



**Fig. 2.** The electron density observations onboard Kosmos-1809 on 1991/05/18 along the orbit at altitude 950 km above the station MIR take-off: upper panel shows the electron density *N*; bottom panel shows the relative electron density *δN/N*.

## Probable physical mechanisms of excitation of ionospheric turbulence during rocket transit

The local turbulization of ionospheric plasma can occur in a neighborhood of the moving space vehicle. However, there are mechanisms which may cause the plasma turbulization in a region shifted along the geomagnetic field lines high up from a rocket. The scatter of an exhaust from the rocket engine in the ionospheric plasma generates a local system of electric fields and currents due to the charge separation processes. This mechanism leads to generation of an electromagnetic pulse at the initial stage of the exhaust product scatter. The polarization of an ionospheric "hole" in the background electric field can also generate a system of field-aligned currents at the boundary of the hole. For both mechanisms the local density of the field aligned current may overcome the values sufficient for plasma instabilities to be excited: the ion-sound or the electrostatic ion-cyclotron (EIC) instability. The growth of the EIC wave amplitude can lead to turbulence and the anomalous field aligned electric field in the turbulence region. The field-aligned currents generated by both mechanisms perform the electrodynamic connection between the lower ionosphere and the magnetosphere.

At the initial stage of the fly-apart speed of the flame gas and its density are high, and intensive horizontal currents are generated. Such non-stationary currents generate MHD waves, in particular, Alfven waves. An initial decrease in concentration takes place on the principle of a "snow plough": expanding neutral particles sweep off the background plasma. The main factor responsible for decreased background plasma density, i.e. changes in the photochemistry of the ionized particles, emerges at later times.

Rough estimates may be obtained with the simplified model of fly-apart of the rocket exhaust products. At the initial stage of fly-apart, the pressure P of the exhaust gases is much higher than the background pressure, and the pressure disturbance expands as a weak shock wave. At the very initial stage, all the ionospheric particles are swept from the flame region. Later, the ions are dragged away by the exhaust particles, while the electrons are retained by a magnetic field. So, the charge separation and generation of electromagnetic fields and currents take place. Later on, both electrons and ions are retained by the magnetic field. Estimates show that the duration of initial phase is ~0.1 s and the duration of second phase is ~10 s. A free fly-apart of the combustion products goes on till pressure in the exhaust is comparable with the background pressure and the diffusion begins to play the main role.

To describe the dynamics of an ionized component, the approximation of three-fluid hydrodynamics for cold plasma consisting of electrons, ions and neutrals can be used. The fast expanding waste particles due to the dynamo-effect provide a system of non-closed electric currents in the lower ionosphere and field-aligned current escaping into the upper ionosphere. The estimated field-aligned currents are about $10^{-5}$ A/m$^2$. Such currents may exceeds the threshold necessary for the development of a wide spectrum of plasma instabilities, emergence of an anomalous resistance, excitation of field aligned electric fields, which further results in acceleration and precipitation of particles. The lowest threshold has ICI, which spontaneously generate electrostatic emission at the frequencies from oxygen gyrofrequency up to proton gyrofrequency, that is in the band 25-400 Hz.

This physical scenario was confirmed by the active experiments “Waterhole”, where the impact of exhaust products on the ionosphere was simulated by the injection into the auroral ionosphere of gases similar to the rocket exhaust products [*Yau et al.,* 1981; *Yau & Whalen,* 1988]. In these experiments a localized hole with diameter of ~5-30 km with steep decrease of N was observed several sec-min after injection. The plasma density recovered after several hours. Steep local depression of *N* stimulated a significant decrease of the auroral arc intensity, occurrence of intense electromagnetic pulse (~260 nT), and generation of turbulence with frequencies about few hundred Hz.

The rocket passage through the ionosphere with operating engine may cause even more pronounced disturbances in the ionospheric dynamics. The intensive local drop produced in the plasma density can act as a prime disturbance for development of a cascade of instabilities (e.g., Raleigh-Taylor) which cover a much larger ionosphere region. In this sense, the rocket's passage through the ionospheric plasma leaving a region of a turbulent trail, is similar to a flight of a jet aircraft in the overcooled atmosphere layers, leaving a cloudy trail behind it. Though a rough model of the rocket impact on the ionosphere was outlined, but the well-justified models of the whole complex of phenomena occurring during the flight of rocket through the ionospheric plasma have not been elaborated so far.

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